NASA TMX 57219

MEASUREMENT OF ANTENNA IMPEDANCE IN THE IONOSPHERE I. OBSERVING FREQUENCY BELOW THE ELECTRON GYRO FREQUENCY

by

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ABSTRACT

18196

The problem of the behavior of an antenna in a magneto-ionic medium is very briefly reviewed. Experimental measurements of both the resistive and reactive components of the impedance of a short dipole in the lower ionosphere are reported for the range of conditions corresponding to $0<X<3$ and $1<Y<1.5$. The antenna reactance is found to decrease with increasing $X=(\omega_p/\omega)^2$ whereas the resistive part of the antenna impedance is found to be many orders of magnitude greater than its free space value for $X\geq1$. Only qualitative agreement is found between experiment and theory. The significance and possible interpretation of the large real component of impedance are discussed.

author

N67-18196 (ACCESSION NUMBER)
25 (PAGES)
TMX-57219 (NASA CR OR TMX OR AD NUMBER)
(THRU)
1 (CODE)
07 (CATEGORY)
FACILITY FORM 602

HC $3.00
MF .65

1. INTRODUCTION

Although there has been extensive theoretical and experimental study of the propagation of radio waves through a magnetically biased plasma, considerably less is known about the situation when the source of radiation itself is in the medium. This is an important problem from both a theoretical and a practical point of view since, for example, antennas are used on rockets and satellites in the ionosphere for plasma diagnostics as well as for the transmission and reception of radio signals. Theoretical analysis of the problem is complicated since propagation from a finite current source inside the plasma must be considered. The simpler problem is concerned only with plane wave propagation in an infinite homogeneous plasma where the source is assumed to be far removed from the region under consideration. In spite of these difficulties, a number of theories have been developed which consider the impedance and radiation characteristics for small antennas in a magneto-ionic medium. In this and subsequent papers, some of these theoretical models will be compared with rocket measurements of the resistive and reactive components of the driving point impedance of a short dipole in the ionosphere.

In this paper, measurements corresponding to the magneto-ionic condition $Y>1$, i.e. observing frequency slightly less than the electron gyro frequency, are considered. In particular, the variation of impedance for observing frequencies close to the electron plasma frequency ($X \sim 1$) will be discussed. One of the most interesting aspects of the problem is the prediction, for certain values of the gyro and plasma frequencies, of a large resistive component of impedance. This resistance, which may be many orders of magnitude greater than the free space radiation resistance of the antenna, may reflect the existence of large radiation or dissipative losses in the medium. We shall review these possibilities in more detail later in the paper.

The free space properties of dipole antennas are reasonably well understood. Their impedance characteristics in the ionosphere are considerably more complicated, however, because the earth's magnetic field renders the plasma anisotropic and birefringent. Furthermore, the presence of the antenna itself disturbs the local properties of the ambient plasma. The difference in mobility of electrons and ions leads to the formation of an ion sheath about the antenna and rocket. Moreover, the sheath distribution can be modified by the electromotive force generated by the motion of the rocket through the earth's magnetic field. The motion of the rocket through the ionosphere can also produce a wake behind the vehicle in which there is a depletion in the number of electrons and ions. This can lead to a "shadowing" of part of the antenna structure by the rocket. These effects can exert a considerable influence on the measured impedance and are difficult to account for theoretically. Some of these interactions will be discussed in a subsequent paper.

There are a number of theories currently available which consider the impedance and radiation characteristics of "short" dipoles and monopoles in a uniform magneto-ionic medium. For the most part these theories do not consider the disturbances in the ambient plasma caused by the antenna itself. Furthermore it is generally assumed that the radio frequency excitation level is sufficiently low so that non-linear effects do not occur.

The far field of a Hertzian dipole in a homogeneous magneto-ionic medium has been investigated by Bunkin(1), Kuehl(2), Arbel(3) and Wu(4) while the near field structure has been studied by Mittra and Deschamps(5). The dipole radiation resistance term has been determined by Kogelnik(6), and his results have been studied and evaluated numerically by Weil and Walsh(7).

Evaluation of the full impedance has been obtained by a number of investigators(8-13). Quasi-static theory, for example, has been used by Kononov et al(8), Kaiser(9), Balmain(10) and Herman(11). Bramley(12) has obtained results which apply to low density plasmas or to weak magnetic fields. Ament et al[13] obtain results applicable to longer dipoles. For certain ranges of the magneto-ionic parameters, singularities develop in many of the impedance formulations. Under these conditions there are serious questions concerning the validity of the formulation.

In order to investigate certain of the qualitative features of the impedance behavior and to point out where the singularities may occur, the following approximate but simplified expression will be considered.

$$Z = \left[\frac{\ln(\frac{L}{\rho})-1}{j\omega 2\pi\epsilon_o L}\right]\left[\alpha_1(\cos^2\theta + \frac{\alpha_3}{\alpha_1}\sin^2\theta)^{\frac{1}{2}}\right]^{-1} \qquad (1)$$

This formula can be derived from Ament's[13] leading term when the dipole is very short. It can also be obtained under suitable approximations from the results of Balmain[10] or Kaiser[9]. The first bracketed term is the free space reactance of a short monopole of length L, radius ρ, and excited at an angular frequency ω. Under the short dipole approximation used here, the real component of the driving point impedance is zero in free space. The second bracketed term arises from the presence of the magneto-ionic medium. In this term,

$$\alpha_1 = 1 - \frac{XU}{U^2-Y^2},\ \alpha_3 = 1 - \frac{X}{U},\ U = 1 - jZ$$

$$X = (\omega_p/\omega)^2 \quad Y = (\omega_h/\omega) \quad Z = \nu/\omega$$

where ω_p = angular electron plasma frequency

ω_h = angular electron gyro frequency

ν = collision frequency

and θ is the angle between the antenna and the static magnetic field. For comparison between theory and experiment, the full theoretical expressions will of course be used.

Consider the case for a collisionless plasma. From equation (1), it can be seen that the impedance may have a resistive or reactive component depending on the magnitude and sign of α_1 and α_3 and also on the magnitude of the angle θ. Furthermore, the reactance may be either capacitive or inductive. A number of clearly defined regions of impedance behavior can be illustrated graphically on the X-Y^2 diagram shown in Fig. 1. The experimental data to be discussed in this first paper relate to regions IV and V since $Y>1$, $\alpha_1 \geq 0$. (Trajectories for the frequencies of the measurements reported in this paper are shown by the dotted curves.) For $X<1$, $\alpha_3 \geq 0$ so that the reactance will be capacitive for all values of the angle θ. For the particular range of Y involved here, the capacitive reactance is predicted to be less than its free space value. On the other hand for $X>1$, $\alpha_3<0$ so that for a certain range of θ, the impedance may also have a resistive component. (In regions II and III, which will be examined in detail in a later paper, we note that theory again predicts a real component of impedance.) When losses such as result from a collision term are included, a resistive component of impedance can occur in Region IV. Furthermore the singularities occurring, for example, at X=1 become bounded.

2. EXPERIMENTAL MEASUREMENTS

The data presented here were obtained for a 102-inch dipole antenna and associated impedance measuring equipment flown on an Apache rocket (NASA 14.127 GI) launched on 16 July 1964 at 1122 EST from Wallops Island, Va. (lat. = 37.7°N, long. = 77.5°W, dip = 73°). The rocket, which attained a peak altitude of 137 km, was also equipped with solar aspect sensors and magnetometers. An electron density profile was obtained by combining the impedance data, simultaneous measurements of antenna capacitance obtained by a separate R. F. probe and data from the Wallops Island Ionosonde to form a consistent picture.

Four (Raymond Engineering) 48-inch telescoping elements were used to form two orthogonal dipole antenna systems. The antenna elements were stored in their telescoped form parallel to and within the rocket body during launch. At an altitude of approximately 60 km the antennas were deployed and extended. A constant bias voltage of about +4.5 v d.c. was applied between the antenna and the rocket body as a means of minimizing the effects of an ion sheath. Both the real and imaginary components of the driving point impedance were measured periodically at frequencies between 1 and 4 Mc/s. The data presented here were obtained at frequencies of 1.0, 1.1, 1.2, 1.3, 1.4 Mc/s corresponding to $1<Y^2<2.2$. Since the impedance measurements by a particular probe were obtained for four frequencies, measurements at a specific frequency were sampled periodically one fourth of the 1.7 sec. operating duty cycle. Because of this sampling it is possible that some isolated resonance effects may not have been observed.

A signal oscillator at frequency f applies a signal of less than 1v peak-to-peak to a sensor network through a wide-band transformer. A sample of the voltage, V, across the antenna, and the current, I, through the antenna is coupled out of the sensor through another wide-band transformer. The V and I signals are individually mixed with a signal at frequency f_d from a beat frequency oscillator to provide the difference frequency $f-f_d$. The V and I difference signals are individually amplified linearly, rectified and filtered to produce d.c. output voltages proportional to the voltage and current from the sensor network. Furthermore, the V and I outputs of the linear amplifiers are also fed individually to limiter circuits where V and I square waves are generated with the same phase relationship as the V and I sensor network output. A logic circuit forms a pulse train from the V and I square waves, with a duty cycle proportional to the phase difference between these signals. An averaging filter converts this pulse train phase information to a d.c. voltage output. A phase range from $-\pi/2 \leq \phi \leq +\pi/2$ is obtained by delaying the voltage square wave by $\pi/2$ with respect to the current square wave. Thus the zero output occurs when the current lags the voltage by $\pi/2$ and the maximum output occurs when the current leads the voltage by $\pi/2$. A simplified block diagram of the instrumentation is shown in Fig. 2.

Fig. 3 shows the measurements of both the series resistive and reactive components of impedance at the observing frequencies of 1.0, 1.2, and 1.4 Mc/s. Additional measurements made at 1.1, 1.3 Mc/s are consistent with the results shown in Fig. 3 but are not displayed. The raw data show modulation due to the rocket spin; however the results in Fig. 3 have been selected for an angle $\theta \sim 75^{\circ}$. This will have little effect on the analysis in this report. The values indicated have also been corrected to remove the effect of a constant base and cable impedance. In Fig. 3, the reactance at the various frequencies is seen to decrease substantially with the increase of altitude from 90-100 km where the electron density, and thus X, increases rapidly. The relative change in reactance varies systematically with observing frequency. Since the measured reactance is less than the free space reactance, we see that for the conditions of the experiment $C > C_o$, which is unlike the more familiar situation for $X < 1$, $Y < 1$. The resistance, on the other hand, is seen to increase sharply near the altitude at which $X = 1$. It has its largest value around $X = 1$ and decreases rapidly to a lower value for $X > 1$. Even then, however, the resistance is orders of magnitude above the free space radiation resistance of less than an ohm. There are a number of smaller peaks or dips in the data which we believe are related to local variations in the electron density seen by the rocket as it travels through the ionosphere. The magnitude of the peak resistance at $X = 1$ decreases with increasing observing frequency.

In Fig. 4 the measured reactance and resistance have been normalized to the value of the free space reactance and plotted as a function of X. In the altitude range of interest the electron gyro frequency is nearly constant at about 1.47 Mc/s, and hence Y may be considered constant. For comparison, the values of impedance calculated using the expressions derived by Balmain[10] and Herman[11] are also plotted in Fig. 4.

Admittedly, the applicability of the theory for these experimental conditions may not be appropriate. The comparison may be helpful nevertheless in interpreting the results. It is anticipated that a more extensive comparison can be made in the future, when the results of other theories have been programmed. For small values of X, Balmain's theory is in qualitative agreement with the measurements of reactance; however there is no experimental evidence to support the sharp peak in reactance predicted for X=1. Although it is possible that the peak may have been missed due to the sequential manner in which the data from this probe were sampled, no such enhancement was observed by a second probe which continuously measured antenna capacitance on the same flight. Balmain also predicts a substantially higher peak in resistance than was measured near X=1 although the resistance values are in qualitative agreement for large X. The validity of the theory is particularly subject to question in the vicinity of X=1, however. The shape of the curves derived from Herman's expression, on the other hand, compare well with the experiment although the predicted values of both reactance and resistance fall below the measured values. In addition to the problem of the validity of the assumptions in the theoretical calculations which complicate any comparison with measurements, there is a further practical problem. The effects of collisions can not be neglected in this altitude range, and yet the uncertain estimates of collision frequency make a reliable quantitative comparison even more difficult.

3. DISCUSSION

One of the most interesting aspects of this problem is the prediction and significance of a large resistive component of the driving point impedance. A study of the far field for a Hertzian (infinitesimal) dipole in a magneto-ionic medium leads to an infinite radiation under certain conditions even when the medium is considered lossless. This will reflect itself as an infinite radiation resistance when making impedance measurements. The situation of an infinite power flow away from a dipole carrying a finite current can be avoided by assuming losses in the medium. But even this may require dissipative losses infinitely close to the antenna. As shown by Keuhl[2], for example, this infinity occurs because there is a cone of half-angle θ about a dipole aligned along the magnetic field on which the electric field components of the characteristic waves approach infinity where

$$\sin^2\theta = \frac{Y^2-1+X}{XY} .$$

Arbel[3] and others have shown, however, that this infinity can be removed if the dipole has inite dimensions, in which case the power flow will be larg but bounded on this cone. A small but non-zero dimension pole should still give meaningful results for conditions removed from the singularity. This seems to be borne out in the comparisons made in Fig. 4. Staras[14] has demonstrated that the "infinity catastrophe" can be removed by assuming a finite dipole carrying a volume current distribution. It is interesting to note that the radiated power is proportional to $(kl)^2$, where k is the propagation constant, so that for the Hertzian dipole infinite radiated power occurs for directions in which $k \to \infty$. Since the effective wavelength of the radiation in the plasma is $2\pi/k$, the antenna may appear to be infinitely long or, at least in the bounded case, many wavelengths long. Therefore it seems unrealistic to refer to a "Hertzian dipole" under these conditions. In a quasi-static derivation of impedance Balmain[10] has also discussed the significance of a large "radiation" resistance in terms of an electric field produced by an irrotational magnetic field in a magneto-active medium. He points out that, for certain angles, this field can contribute to the Poynting vector power flow. In addition to the difficulties already mentioned, the theoretical models all seem to be based on the weak field approximation. Electric fields at certain frequencies such as the electron plasma frequency will cause local electrons to experience much larger amplitude excursions than will fields of the same strength at frequencies removed from the resonance points. If the effects of fields do build up under such conditions then the representation commonly used for the dielectric tensor will be invalid. Considerations of the far field power flow would tend to support the hypothesis that the resistive component of impedance does in fact represent radiation. However the issue is far from settled. Bramley[15], for example, suggests that a collection of electrons in phase with the RF voltage applied to the antenna could account for a large measured resistance. Plasma longitudinal waves have also been suggested as a source of power loss from the antenna. The fact that the antenna is excited with an RF voltage when its impedance is being measured complicates the problem since this provides a means of coupling to the plasma so that loading by the plasma cannot be ignored. We shall have an opportunity in a later paper to compare impedance measurements and radiometer measurements on the same flight, but for conditions corresponding to $Y<1$.

For the conditions reported here, $1.5>Y>1$, the reactance is capacitive, for all values of X. However for the "whistler" mode, $Y>>1$, there is evidence to suggest that the reactance may change sign. This will be considered elsewhere.

4. CONCLUSIONS

Extensive measurements of antenna impedance in a magnetically biased medium will be required to produce adequate information for the generation of better theoretical models. The interpretation of the resistive term may well require, in the final analysis, far field measurements. In addition, the effects introduced by the presence of the antenna and rocket structure must be understood so that these effects can be separated from the actual problem involving the antenna field interaction with the plasma. We shall have occasion in a future paper to illustrate just how significant many of these perturbing effects can be when high precision measurements are attempted. When these effects are adequately understood, it is possible for example, that the antenna characteristics in a plasma may provide gain and bandwidth capability far surpassing operation in free space.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the contributions of Messrs. J. Guthrie, T. Tepper and A. Parsons for their work on the experimental payload and Mrs. M. E. Sullivan and Mr. G. Prothro for their assistance with the data reduction and the many numerical calculations. They are also indebted to Dr. J. Herman for many useful discussions and suggestions.

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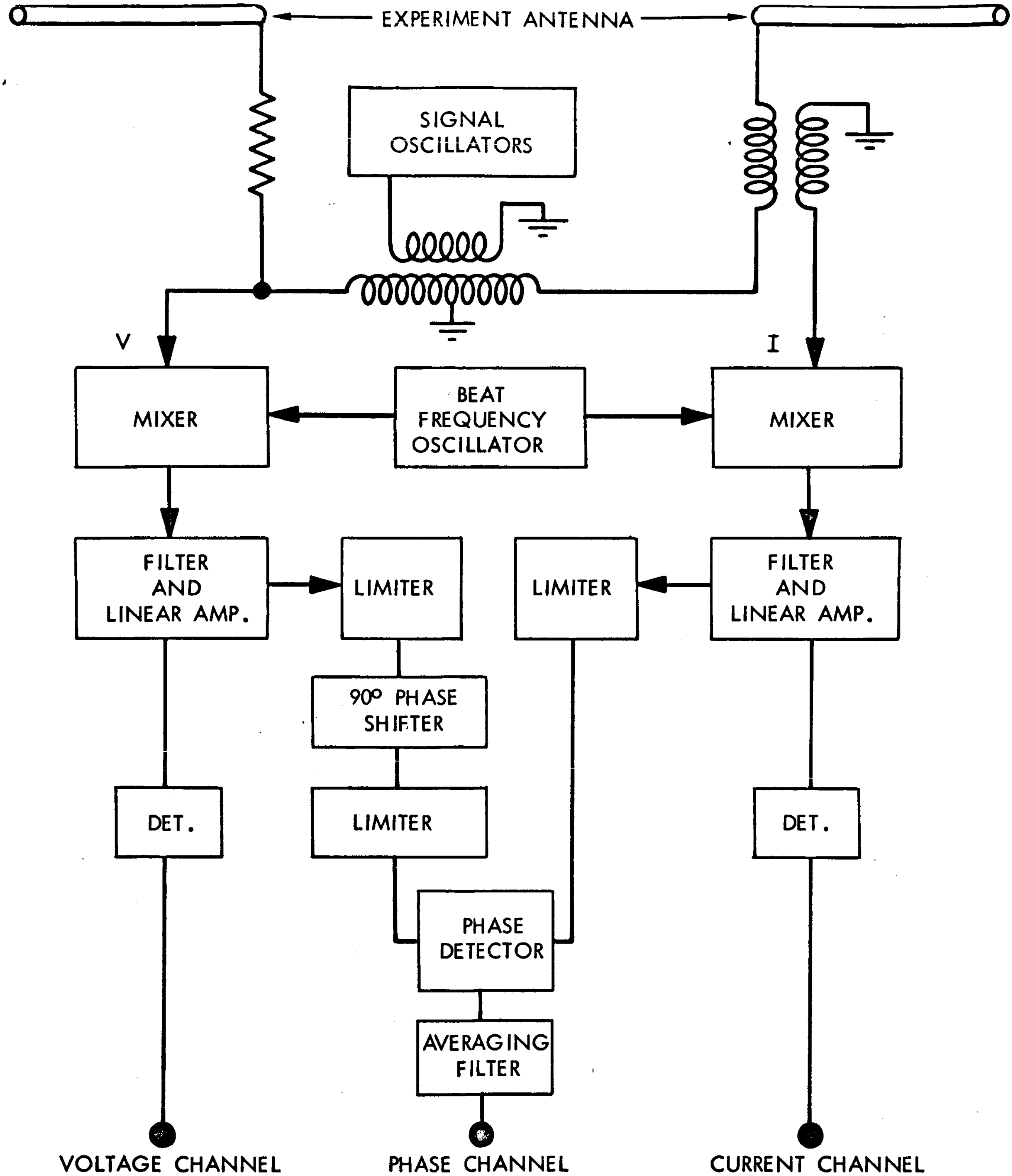
FIGURE CAPTIONS

Figure 1 - An X-Y^2 diagram of the regions of antenna impedance behavior in a plasma showing the trajectories of the experimental measurements. The rocket altitudes in km are shown by the hash marks.

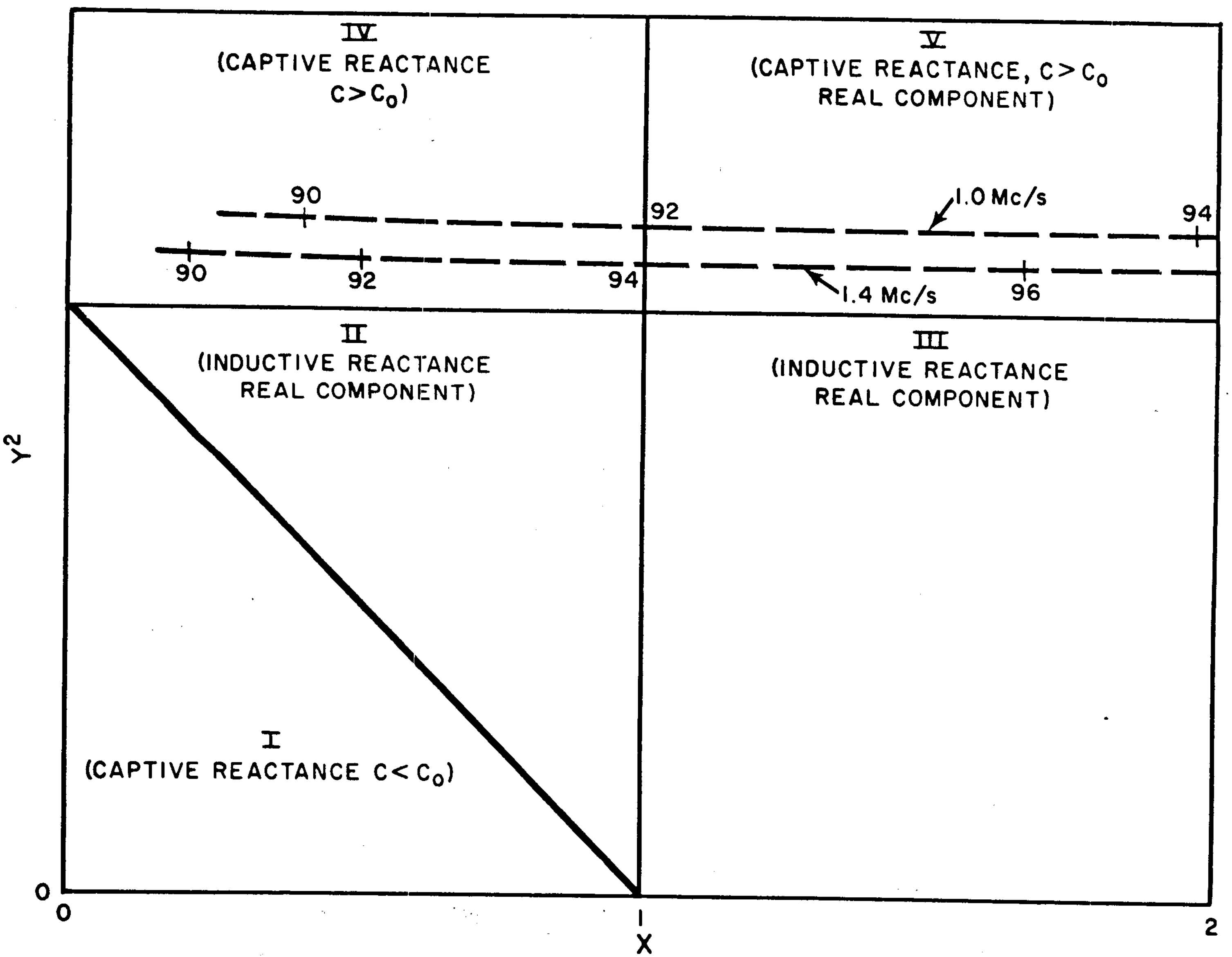
Figure 2 - Block diagram of the antenna impedance probe.

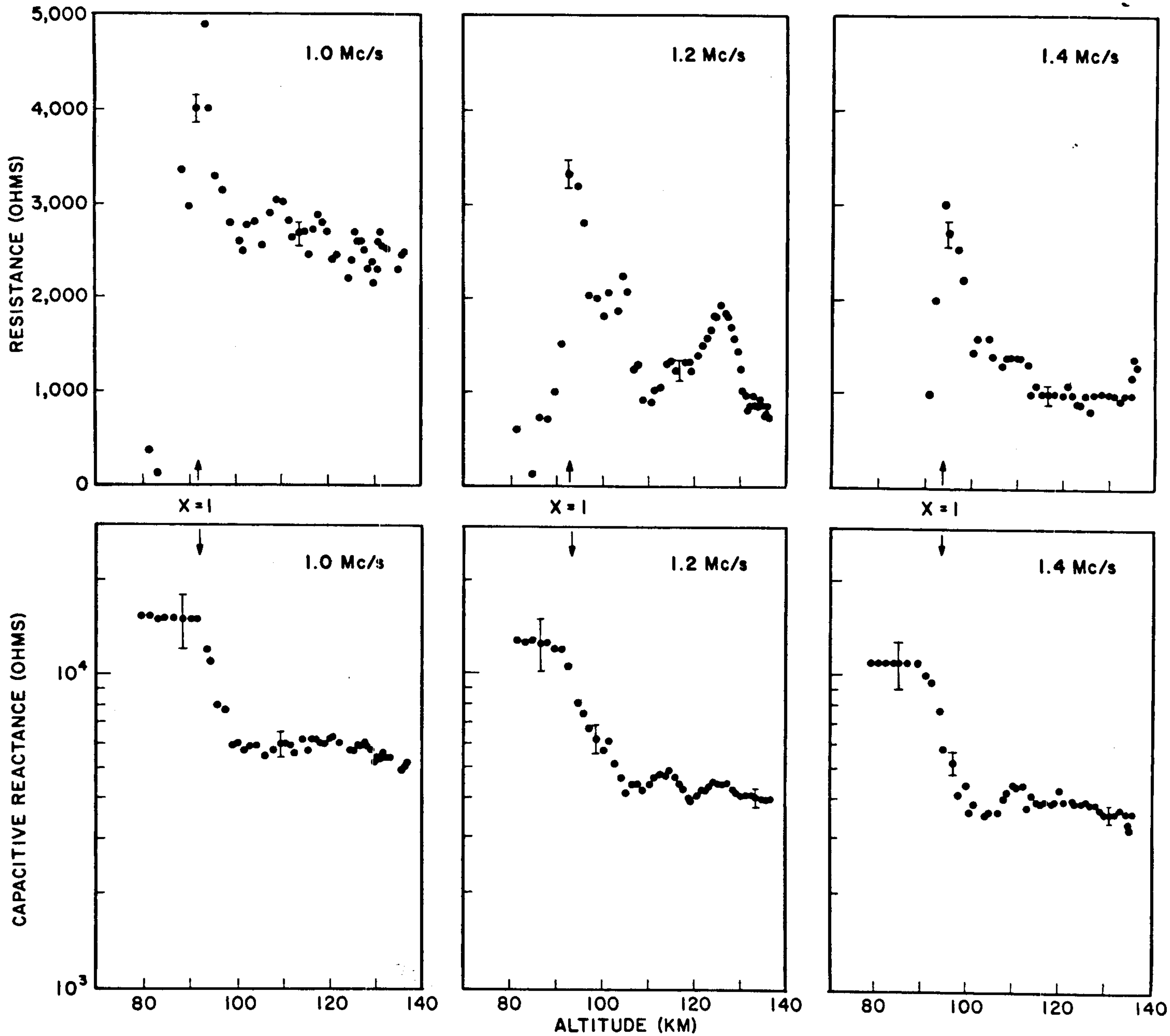
Figure 3 - Measured resistance and reactance of a short dipole in the lower ionosphere averaged over $60^{\circ}<\theta<90^{\circ}$.

Figure 4 - Comparison of measured and theoretical ratios of antenna reactance and resistance to the free space reactance as a function of X. In the case of the measurements, the nearly constant values of Y are 1.47 at 1.0 Mc/s, 1.22 at 1.2 Mc/s and 1.05 at 1.4 Mc/s.

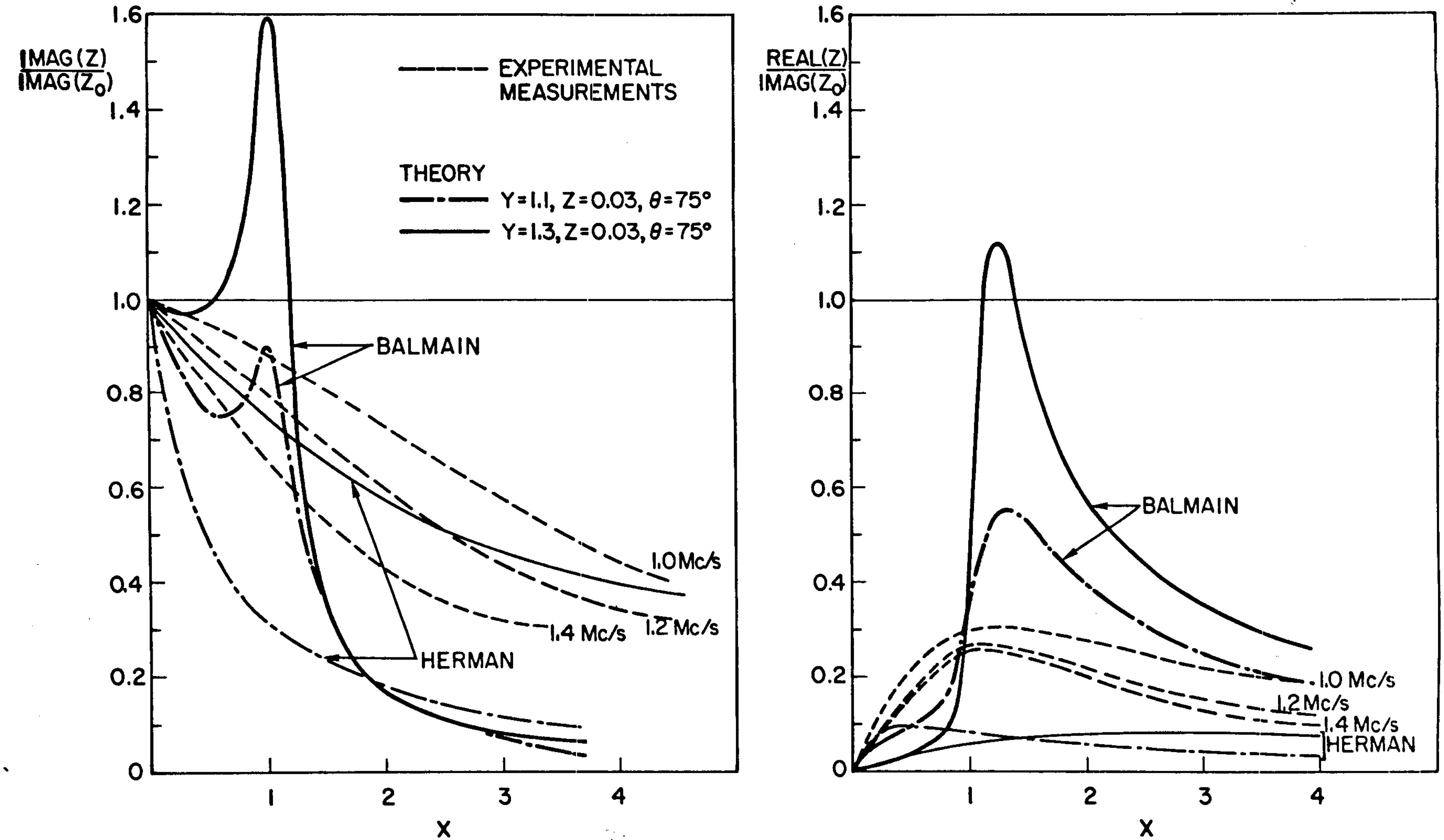


EXPERIMENT ANTENNA
SIGNAL OSCILLATORS
V
I
MIXER
BEAT FREQUENCY OSCILLATOR
MIXER
FILTER AND LINEAR AMP.
LIMITER
LIMITER
FILTER AND LINEAR AMP.
90° PHASE SHIFTER
DET.
LIMITER
DET.
PHASE DETECTOR
AVERAGING FILTER
VOLTAGE CHANNEL
PHASE CHANNEL
CURRENT CHANNEL


IV
(CAPTIVE REACTANCE
C>C0)
V
(CAPTIVE REACTANCE, C>C0
REAL COMPONENT)
1.0 Mc/s
1.4 Mc/s
90
92
94
96
II
(INDUCTIVE REACTANCE
REAL COMPONENT)
III
(INDUCTIVE REACTANCE
REAL COMPONENT)
I
(CAPTIVE REACTANCE C<C0)
Y2
X
0
1
2



RESISTANCE (OHMS)
5,000
4,000
3,000
2,000
1,000
0
1.0 Mc/s
1.2 Mc/s
1.4 Mc/s
X = 1
X = 1
X = 1
CAPACITIVE REACTANCE (OHMS)
10^4
10^3
80
100
120
140
ALTITUDE (KM)



IMAG(Z) / IMAG(Z0)
EXPERIMENTAL MEASUREMENTS
THEORY
Y=1.1, Z=0.03, θ=75°
Y=1.3, Z=0.03, θ=75°
BALMAIN
HERMAN
1.0Mc/s
1.2 Mc/s
1.4 Mc/s
X
REAL(Z) / IMAG(Z0)
BALMAIN
1.0 Mc/s
1.2 Mc/s
1.4 Mc/s
HERMAN
X